Study of QCD phenomena in Z+Heavy-Flavor jet measurements performed on Run-2 ATLAS data at $\sqrt{s} = 13$ TeV

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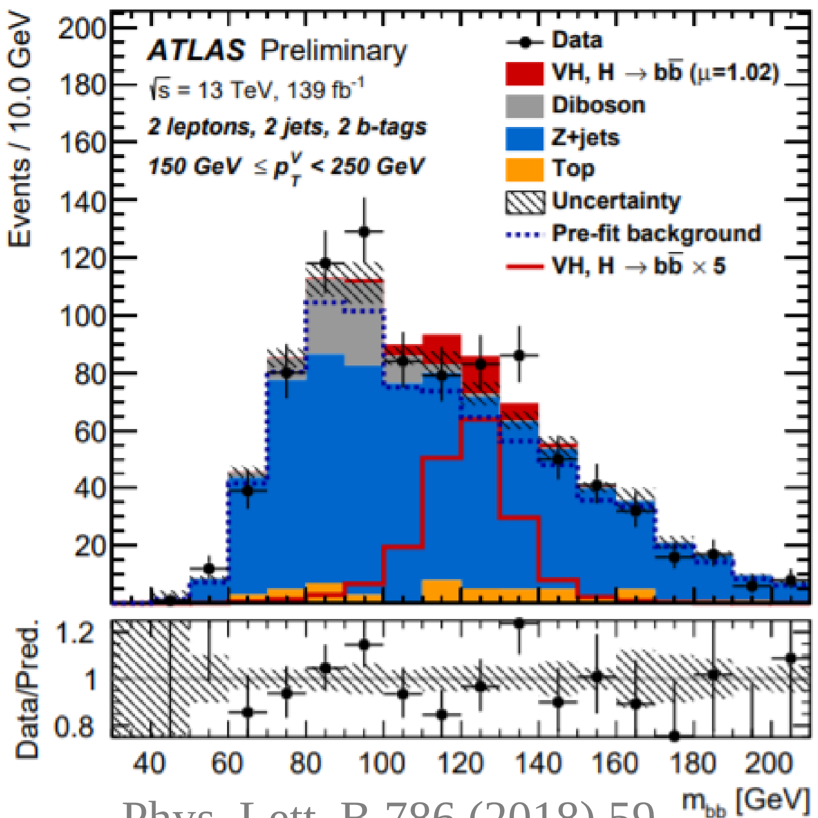
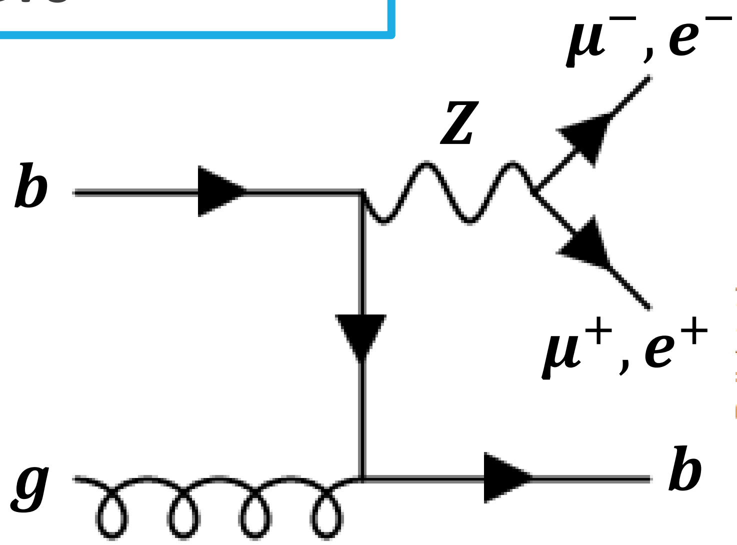
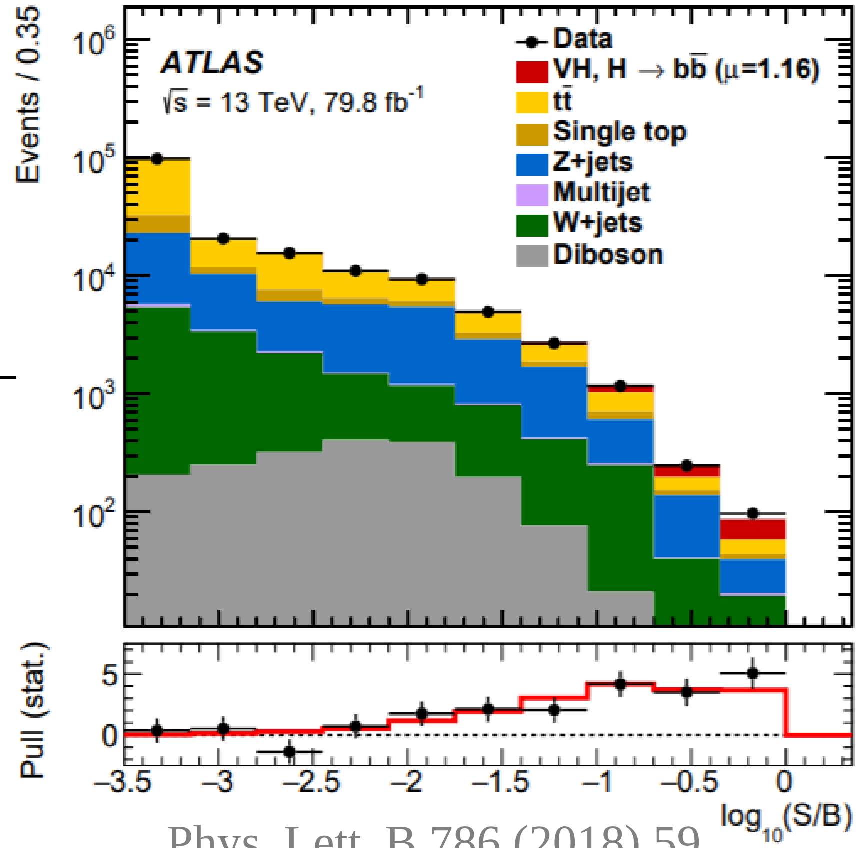
Motivation

- **Test perturbative QCD (pQCD) predictions, particularly those using 4-flavor vs. 5-flavor number scheme**
- **Sensitivity to quark, gluon PDFs**



Phys. Lett. B 786 (2018) 59





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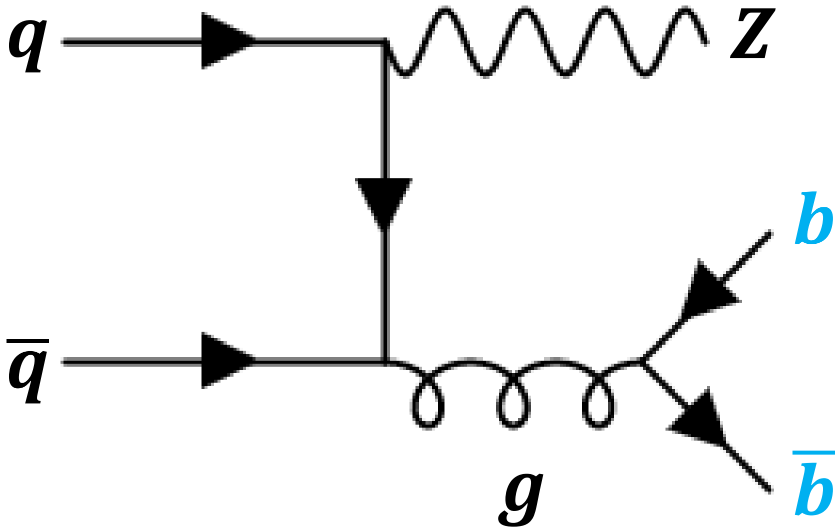
- **Z+HF jets is substantial background to Higgs measurements, BSM searches**
  - VHbb studies limited by systematics of V+HF modelling

Flavor schemes in Z+bjet production

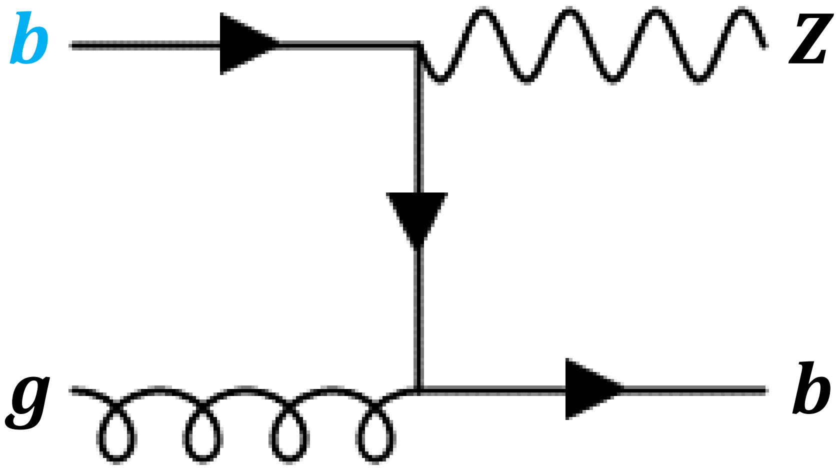
Four-flavor number scheme (4FNS)

- Massive b-quark
- b PDF set to 0
- b quarks only produced in final state through gluon splitting
- Not resummed; requires NLO pertubative calculations



Five-flavor number scheme (5FNS)

- Massless b-quark
- Gluon splitting included in b PDF (initial state)
- (DGLAP) Resummed prediction at LO
- Doesn't describe well phase space regions where m_b is relevant

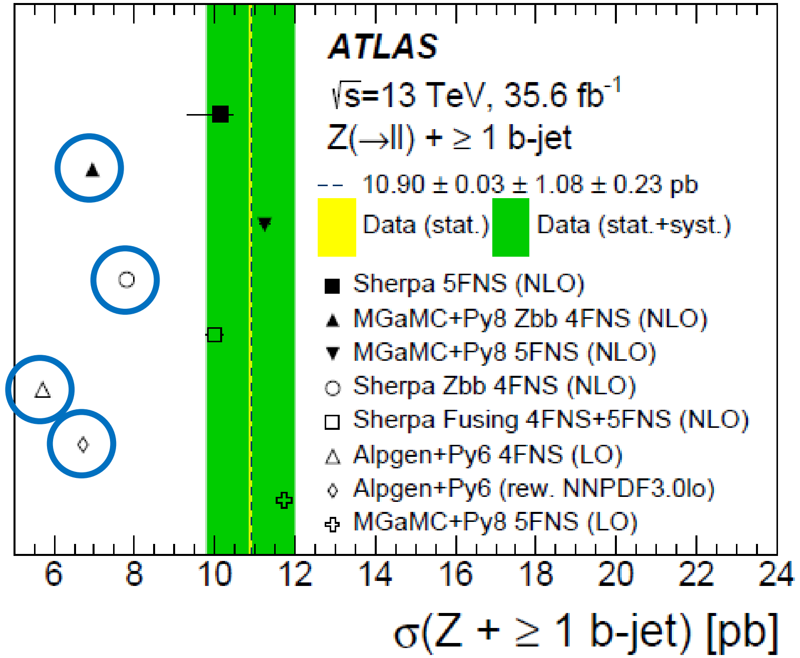


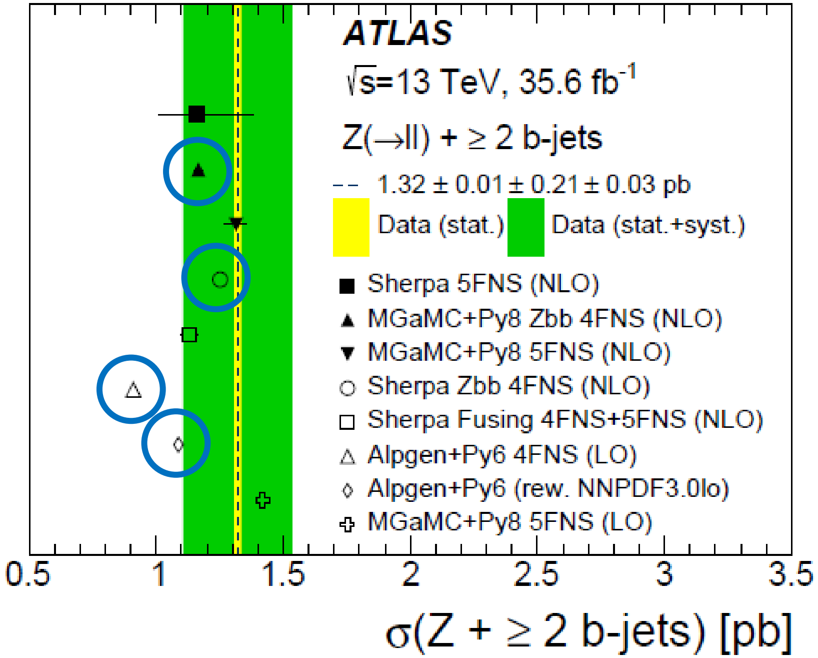
Previous Analysis

- Run-1 data ($35.6\ \mathrm{fb}^{-1}$) at $\sqrt{s} = 13$ TeV
- ≥ 1b-jet and ≥ 2b-jet signal regions (jets: $p_\mathrm{T} > 20$ GeV and rapidity $|y| < 2.5$)
- Inclusive and differential cross-sections compared against various theoretical predictions

Generator	$N_{\max}^{\text{partons}}$ NLO	$N_{\max}^{\text{partons}}$ LO	FNS	PDF set	Parton Shower
Z+jets (including Z+b and Z+bb)					
Sherpa 5FNS (NLO)	2	4	5	NNPDF3.0nnlo	Sherpa
Sherpa Fusing 4FNS+5FNS (NLO)	2	3	5 (*)	NNPDF3.0nnlo	Sherpa
Alpgen + Py6 4FNS (LO)	-	5	4	CTEQ6L1	Pythia v6.426
Alpgen + Py6 (rew. NNPDF3.0lo)	-	5	4	NNPDF3.0lo	Pythia v6.426
MGaMC + Py8 5FNS (LO)	-	4	5	NNPDF3.0nlo	Pythia v8.186
MGaMC + Py8 5FNS (NLO)	1	-	5	NNPDF3.0nnlo	Pythia v8.186
Z+bb					
Sherpa Zbb 4FNS (NLO)	2	-	4	NNPDF3.0nnlo	Sherpa
MGaMC + Py8 Zbb 4FNS (NLO)	2	-	4	NNPDF3.0nnlo	Pythia v8.186

- *(left)* **4FNS** underpredicts ≥ 1b-jet cross-section, while 5FNS does well
- *(right)* For ≥ 2b-jet results, 4FNS predictions improve

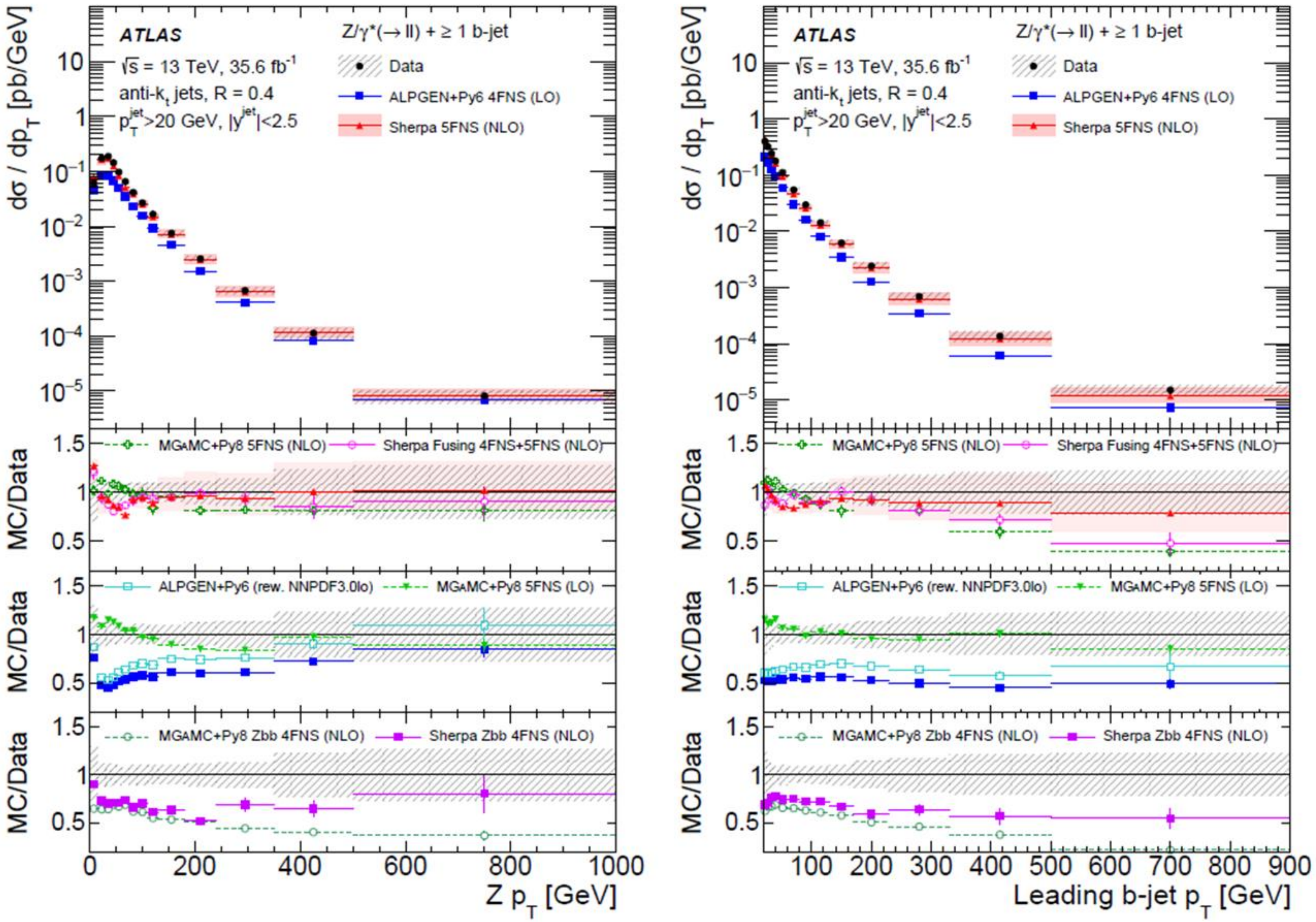




JHEP 07 (2020) 044

Previous Analysis

- **4FNS** (Alpgen+PY6, blue squares) consistently underpredicts differential cross-sections for p_{T}^{Z} *(left)* and leading b-jet p_{T} *(right)*
- **5FNS** (Sherpa, red triangles) does much better



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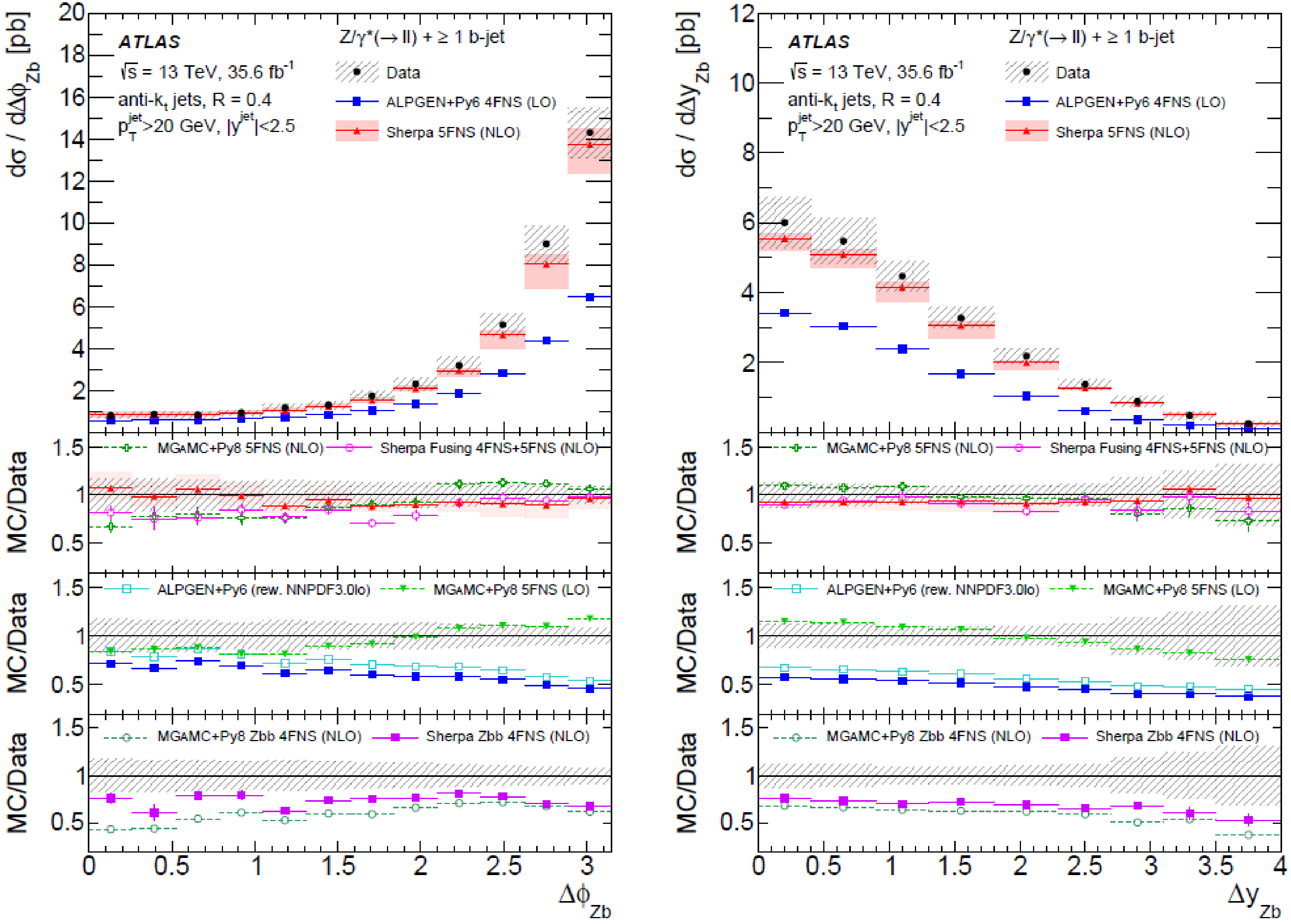
Previous Analysis

- In particular, angular separation variable such as $\Delta\phi_{Zb}$ *(left)* and ΔY_{Zb} *(right)* show large differences between predictions



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This Analysis

The current Z+HF Run II analysis will complement the previous analysis in a number of ways:

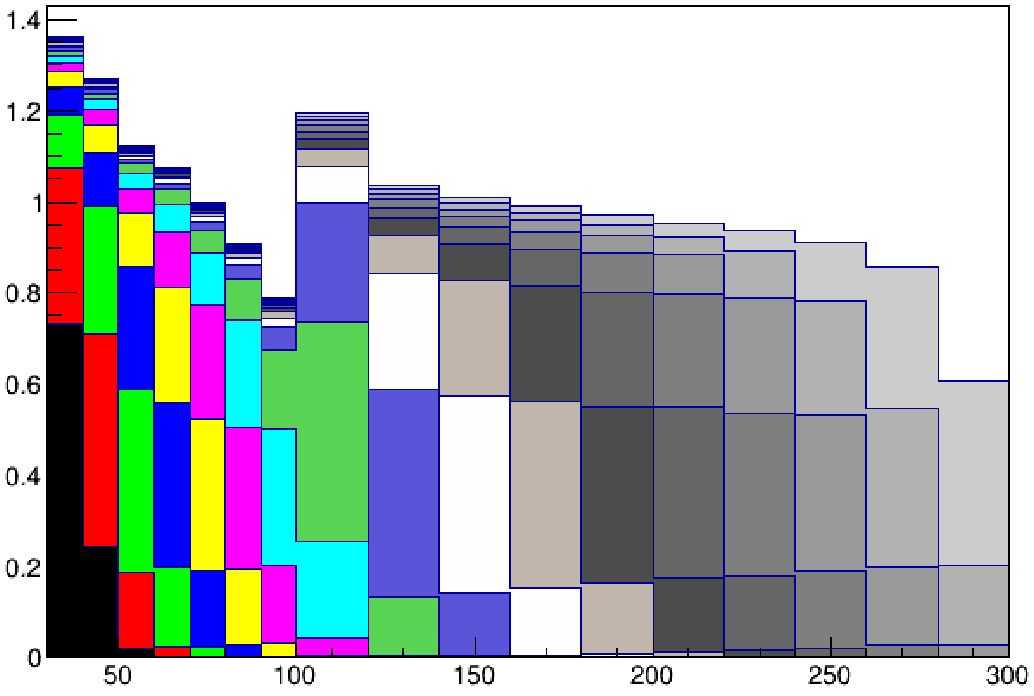
- **$\sim$4x larger integrated luminosity ($140\ \mathrm{fb}^{-1}$) with addition of 2017 and 2018 data**
  - Relevant in particular for p_{T}^{b}, $|\eta|$, Z+bb, Z+c(c)
- **Improvements available in Run II ATLAS software (e.g. tagging)**
- **Additional focus on observables sensitive to intrinsic charm**
  - Z+c(c) and Z+c/Z+b ratios
  - Potential to look at b+c (HF) signal region – better purity, smaller flavor-tagging, fit uncertainties

Current studies which I'll mention here:

1. Fitting and Unfolding
2. Flavor separation
3. Intrinsic Charm

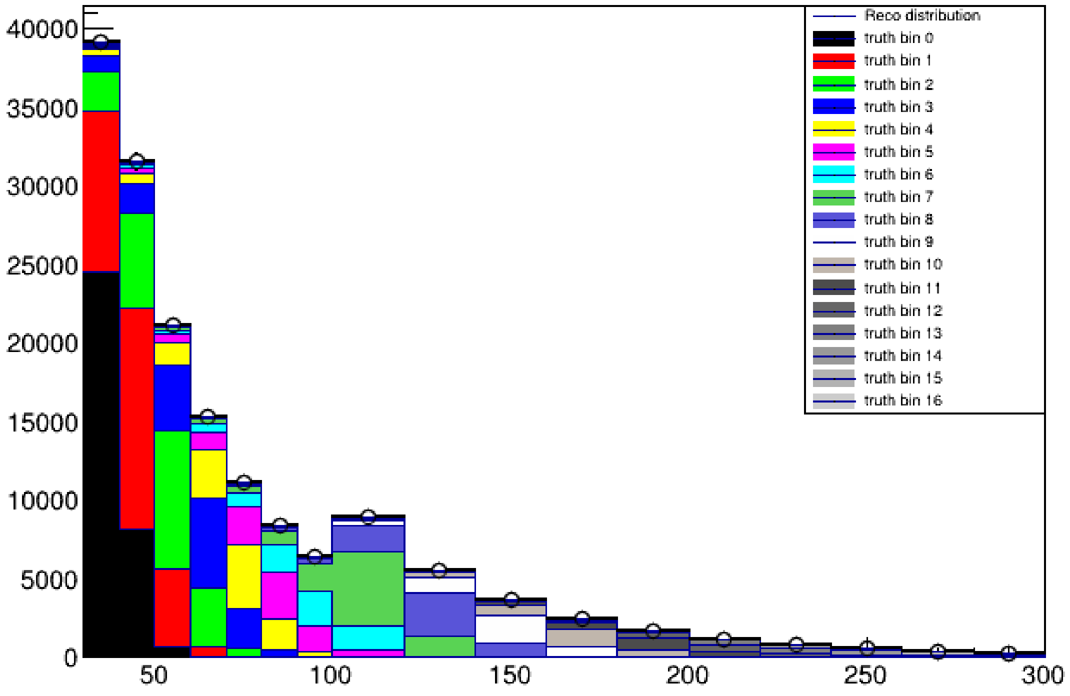
1. Fit & Unfold

- Normally, **a fit on the MC would be performed**, and then the results would be unfolded



Probability for particle in given truth bins (colors) to be reconstructed in each reco bin

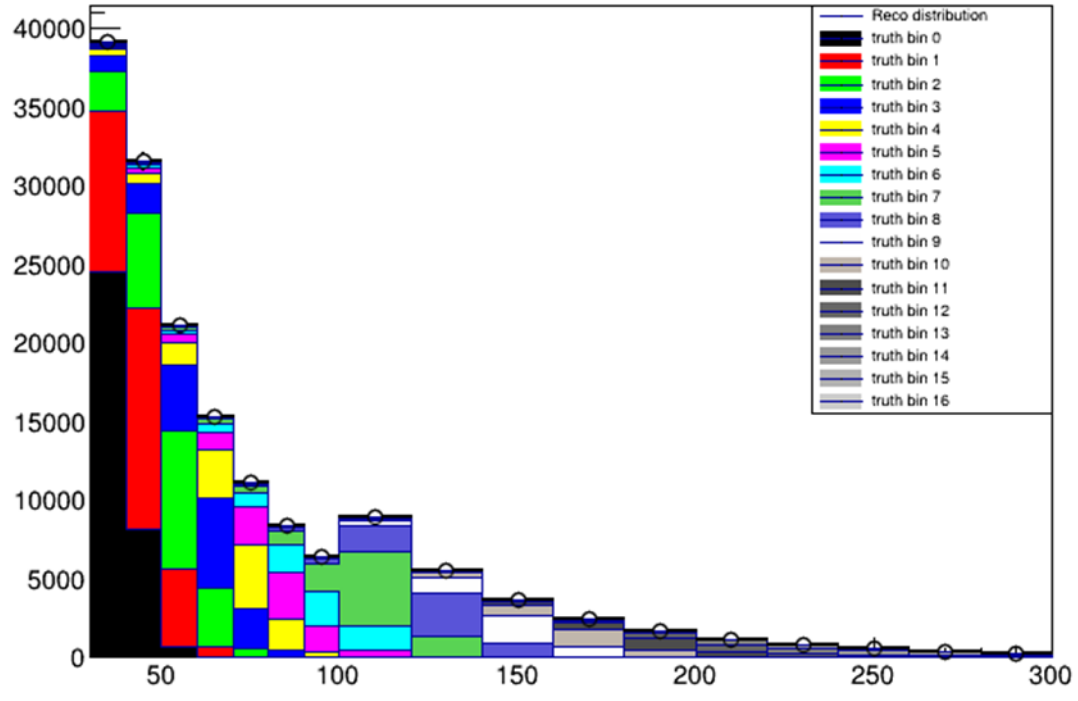
Normalize with number of truth events



Fitted reco distribution

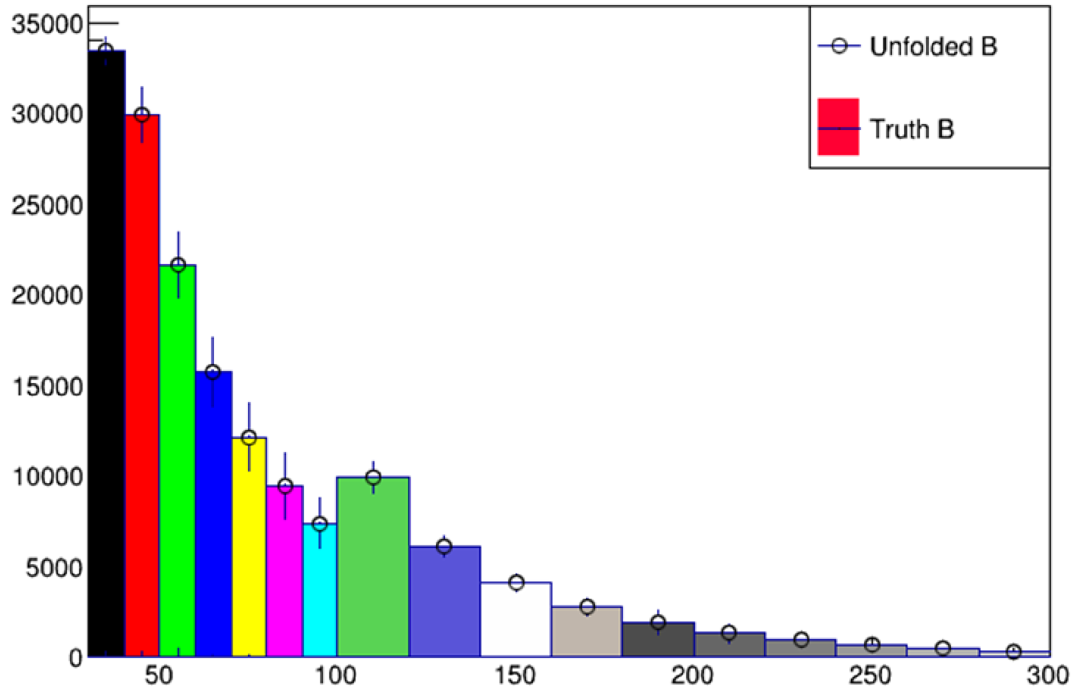
1. Fit & Unfold

- Normally, a fit on the MC would be performed, and **then the results would be unfolded**



Fitted reco distribution

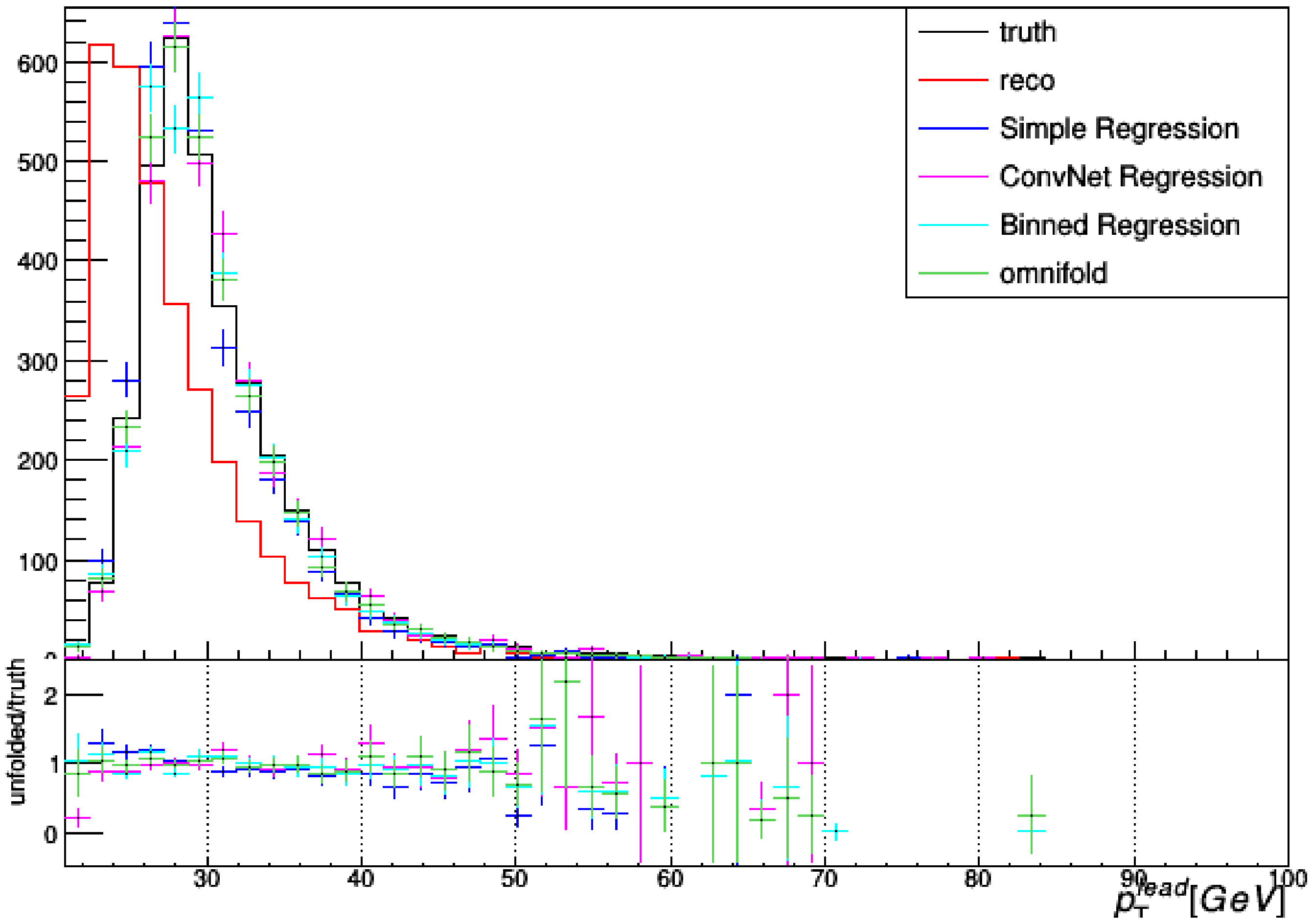
Unfold



Unfolded reco distribution – for each bin, reco events match those in truth (closure)

1. Fit & Unfold

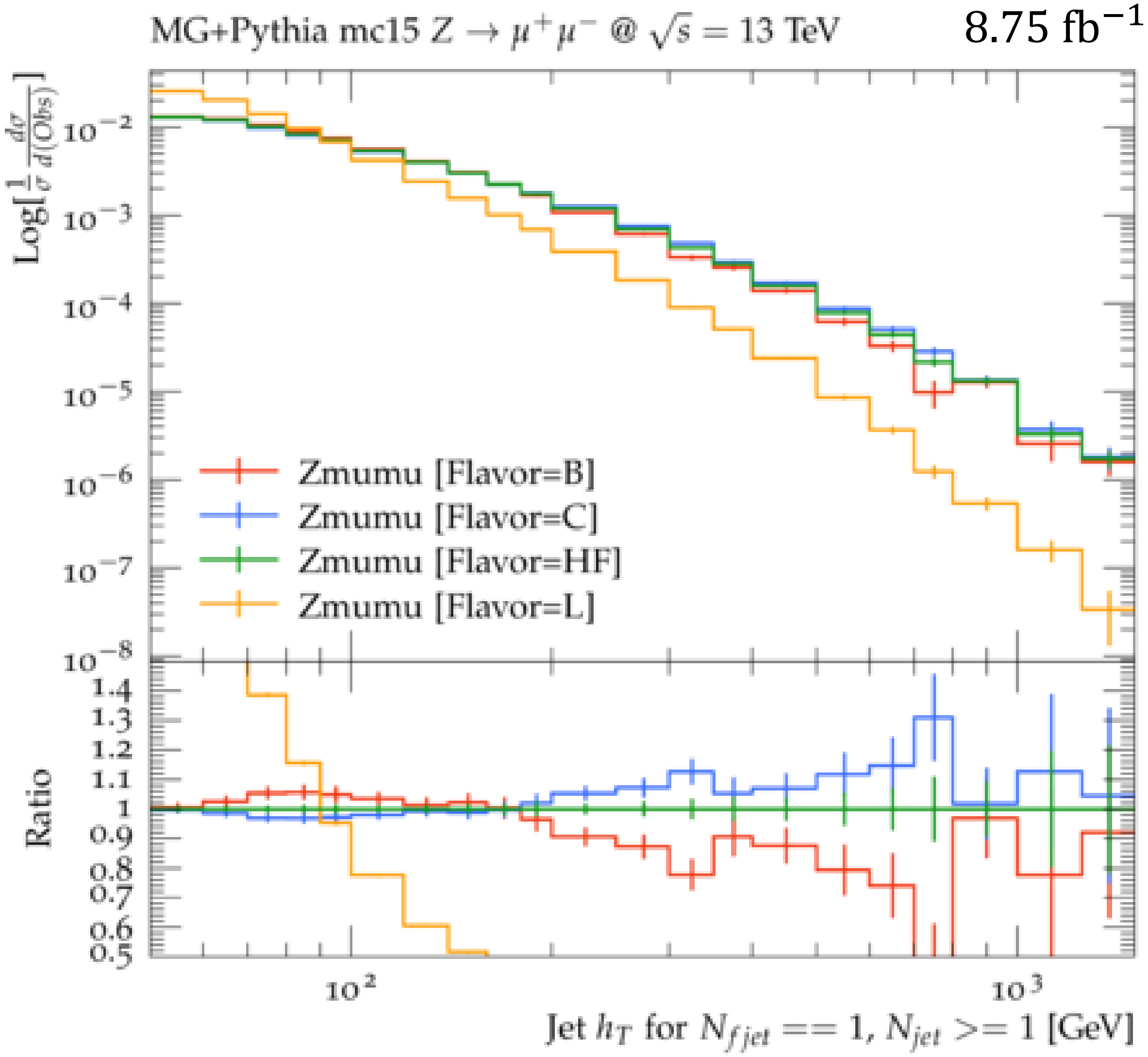
- We can, instead, perform the fit and unfolding simultaneously. One way to do this is using machine learning *(right)*
- Pros:
  - As opposed to sequential fit-then-unfold, MC truth only used for unfolding
  - Preserves correlations between observables
- Cons:
  - Slow, computationally intensive
  - If using ML: what are the errors?



2. Flavor Separation

- In Rivet, separated flavor jets into regions
  - **B** (≥ 1 bjet, 0 cjet)
  - **C** (≥ 1 cjet, 0 bjet)
  - **HF** (≥ 1 bjet and/or ≥ 1 cjet)
  - **L** (No bjets or cjets)
- Selections:
  - Z: $71 < m_Z < 111$ GeV
  - Leptons: $p_{\mathrm{T}} > 28$ GeV && $|\eta| < 2.5$
  - Jets: $p_{\mathrm{T}} > 20$ GeV && $|y| < 2.5$

- Good separation between **HF** and **L** for:
  - **Jet h_{T} for == 1 flavor jet, ≥ 1 overall jet *(right)***



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- Good separation between **HF** and **L** for:
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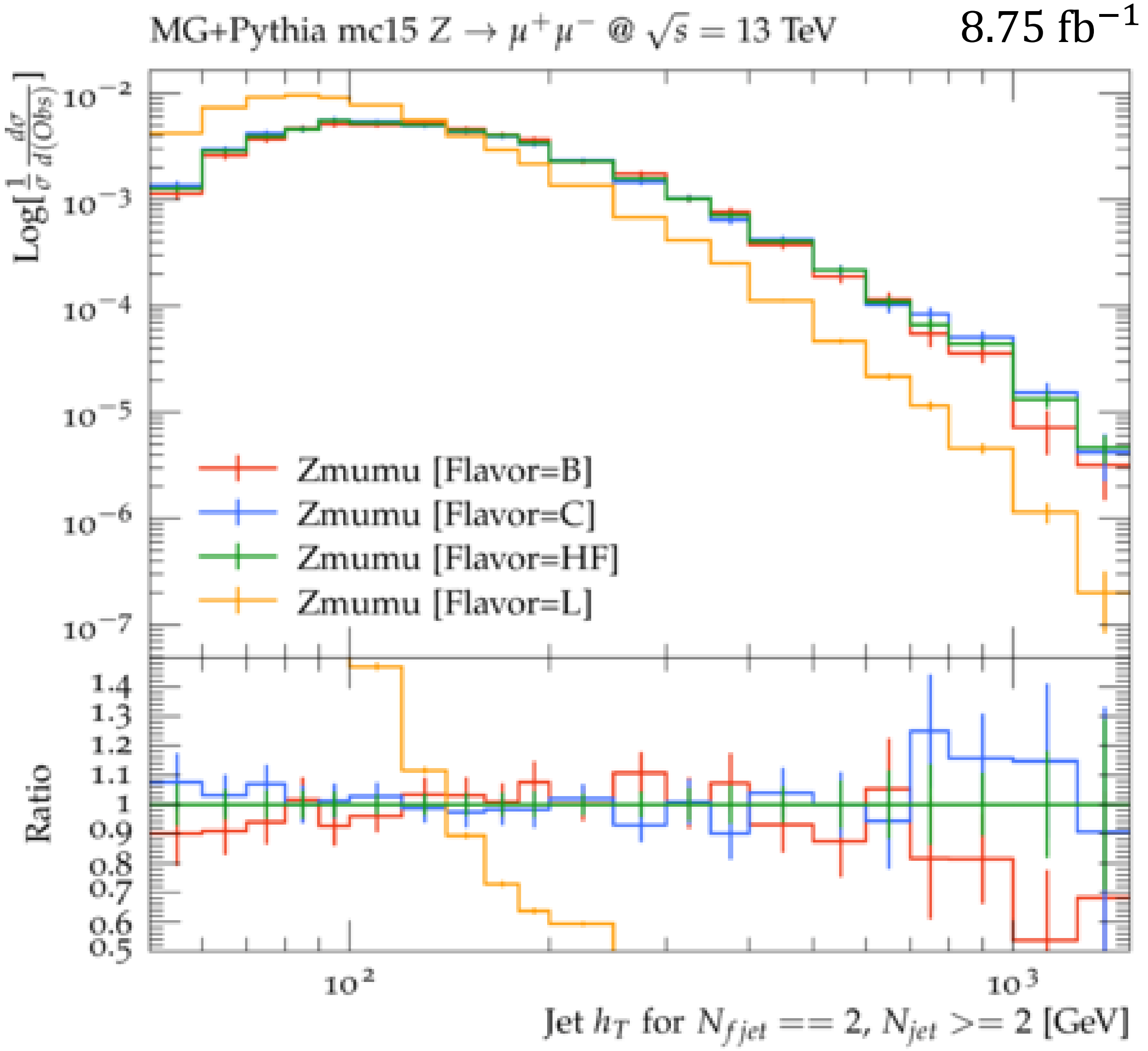
  - **Jet h_T for == 2 flavor jet, ≥ 2 overall jet *(right)***



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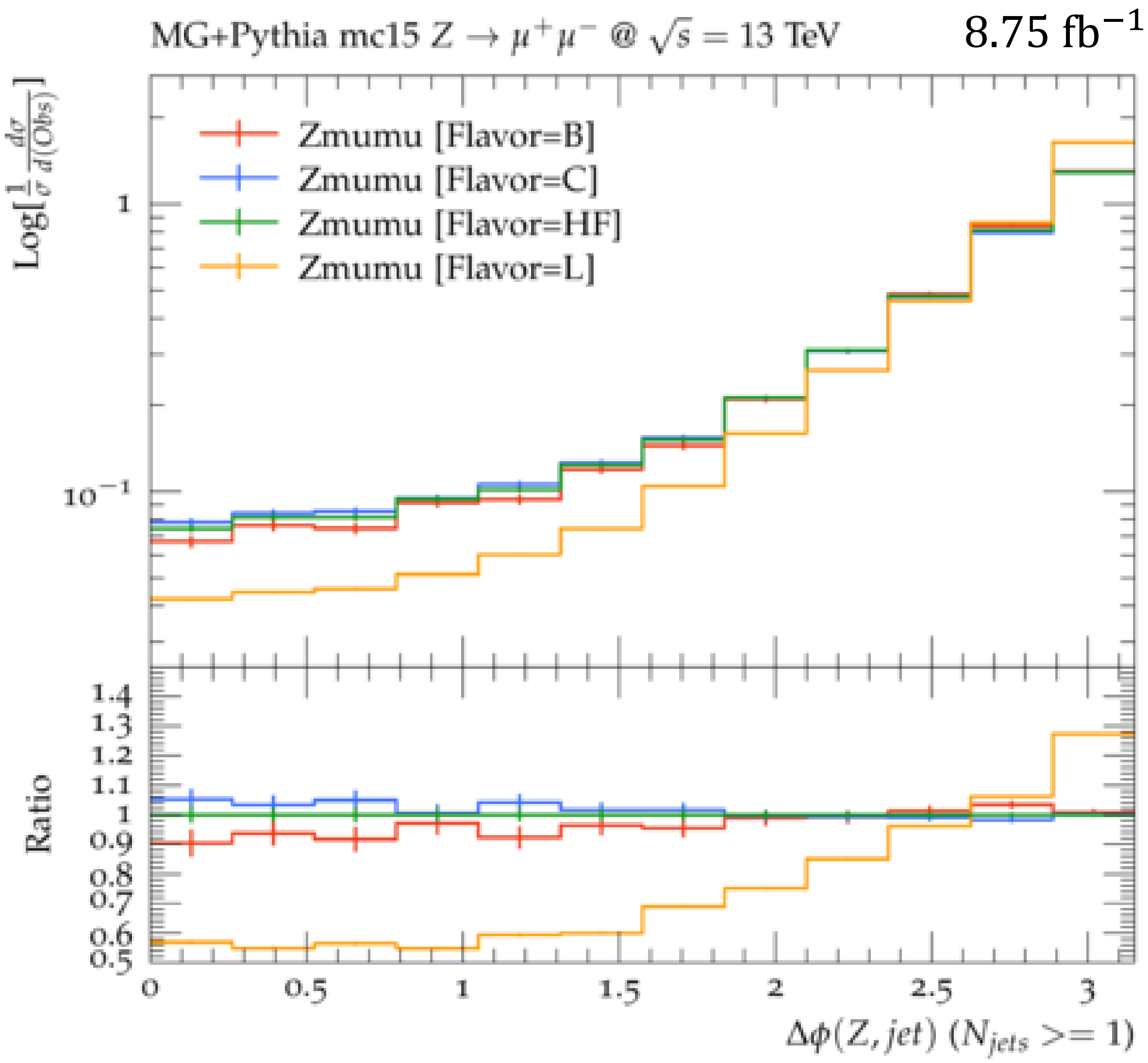
  - *Jet h_T for == 2 flavor jet, ≥ 2 overall jet*
  - **$\Delta\phi_{Z,\mathrm{jet}}$ for ≥ 1 flavor jet *(right)***



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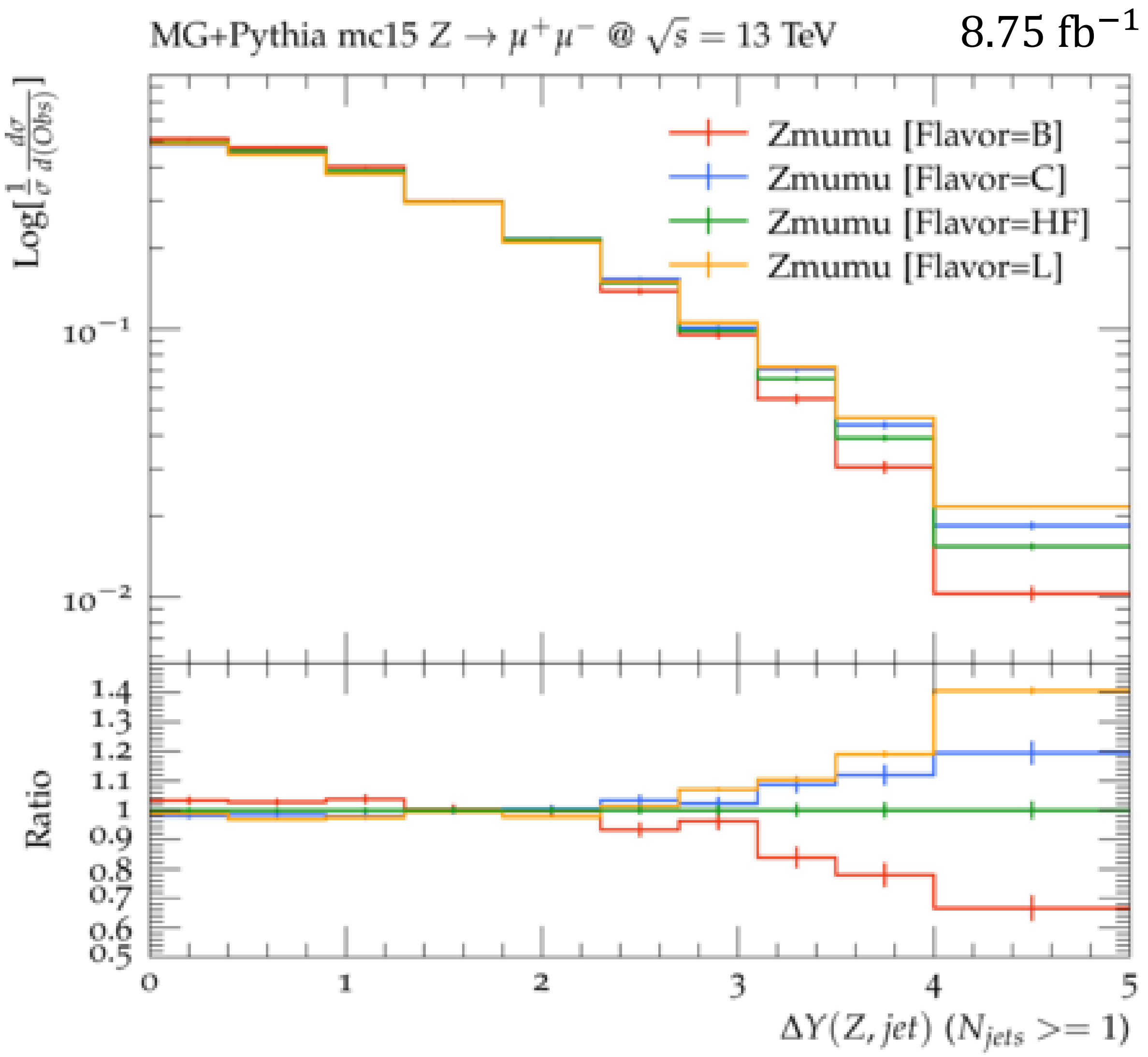
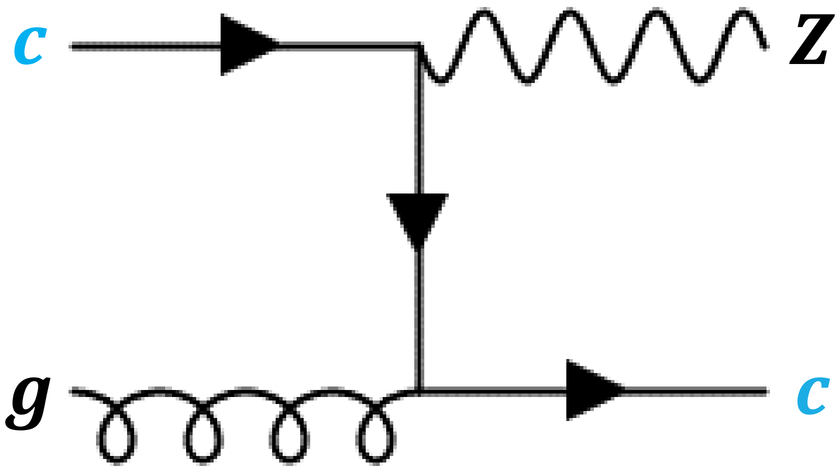
- Limited separation between **B** and **C** for:
  - $\Delta y_{Z,\mathrm{jet}}$ for ≥ 1 flavor jet *(right)*



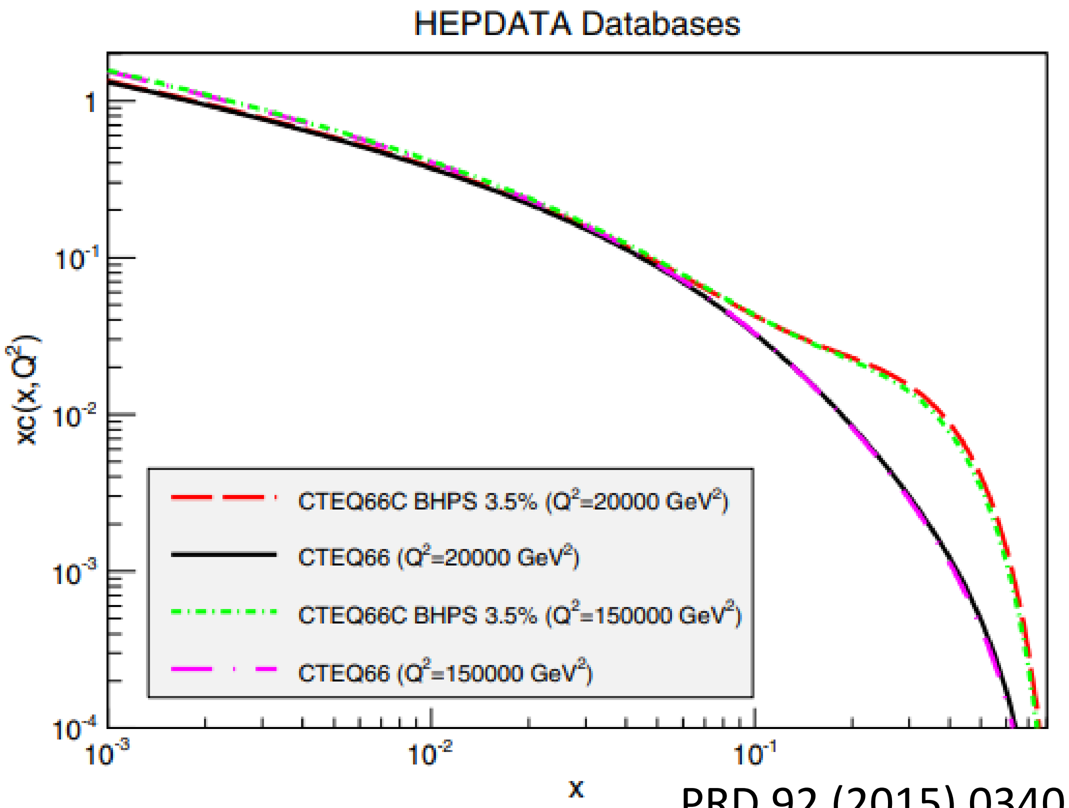
3. Intrinsic Charm

Intrinsic charm (IC) contribution to proton PDF could describe charmed hadron production in ISR

- CTEQ *(right)* and NNPDF provide PDF sets with option to include IC according to Brodsky-Hoyer-Peterson-Sakai (BHPS) model [PLB 93 (1980) 451]



$|uud c\bar{c}>$ Fock component to wavefunction



PRD 92 (2015) 034014

- IC quarks have large x compared to sea quarks → forward Z with hard cjet
- Can result in 1.5-2x more Z+cjet events [PRD 92 (2015) 034014]

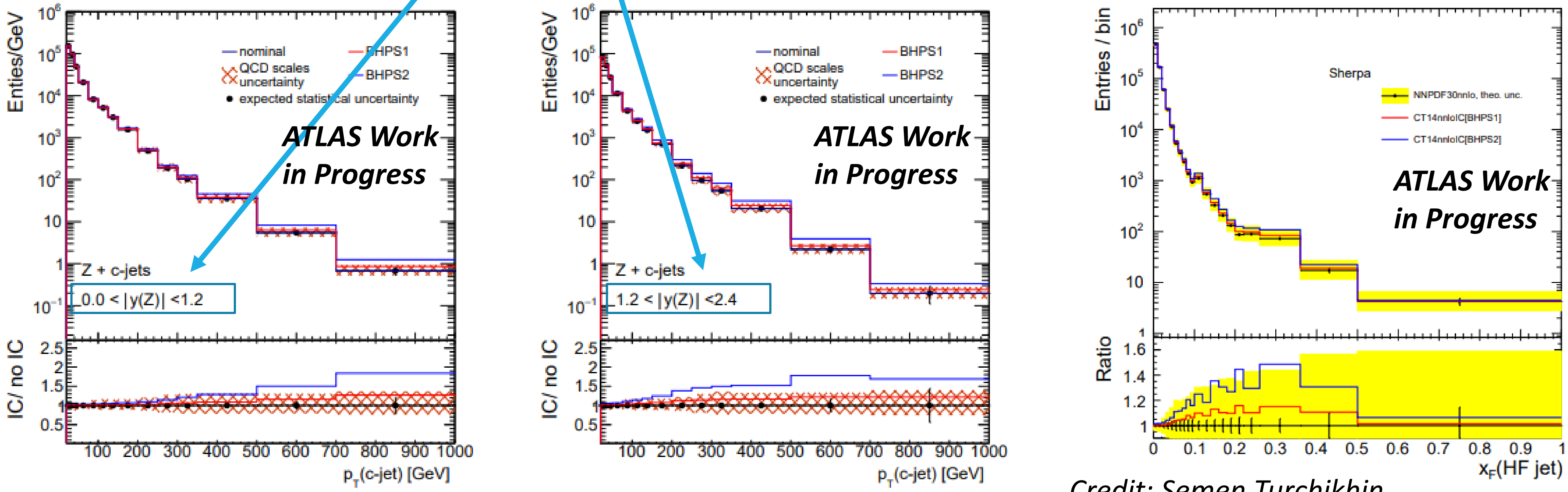
3. Intrinsic Charm

Observables *(normalized to 140 fb^{-1}):*

- p_{T} of heavy-flavor jet *(left)*, particularly at > 200 GeV
  - y-selection to also be tuned *(middle)*
- $x_F = \frac{2p_{\mathrm{T}}\sinh(y)}{\sqrt{s}}$ *(right)*

These plots:

- Truth-tagged c jet events
- Using pseudo-continuous b-tagging
- See ~40% effect for both p_{T} and x_F



Credit: Semen Turchikhin

Summary

- This analysis (Z+HF, Run II) looks to build on the results of the Run I Z+bjet analysis, with more data and refined techniques
  - $140\ \mathrm{fb}^{-1}$ of 2015-2018 data
  - Improved fitting and unfolding techniques
  - Investigations of observables sensitive to B vs. C as well as HF vs. L separation
  - Possible sensitivity to intrinsic charm

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